Status of the Mu2e experiment

S. Di Falco
INFN Pisa
on behalf of the Mu2e Collaboration

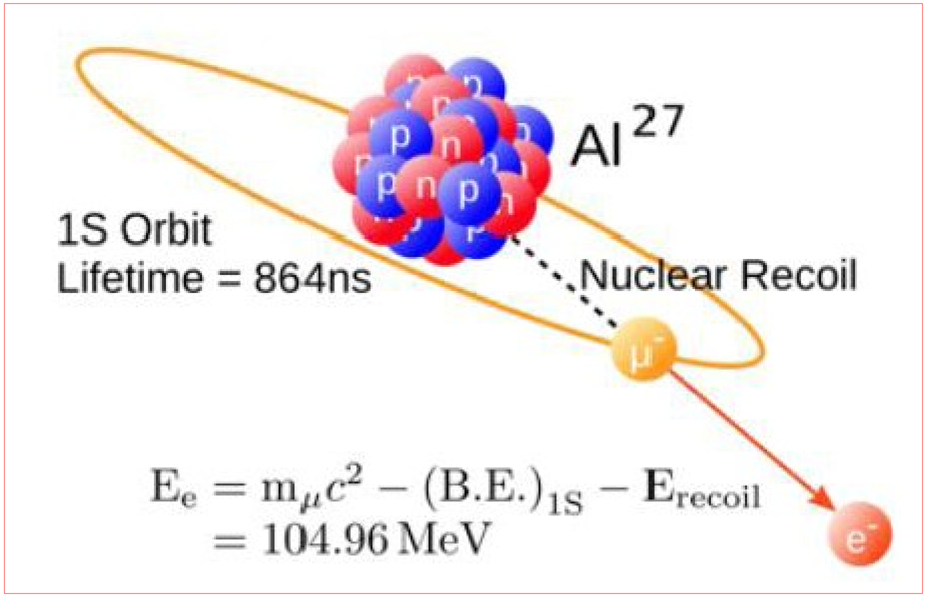
The Mu2e experiment

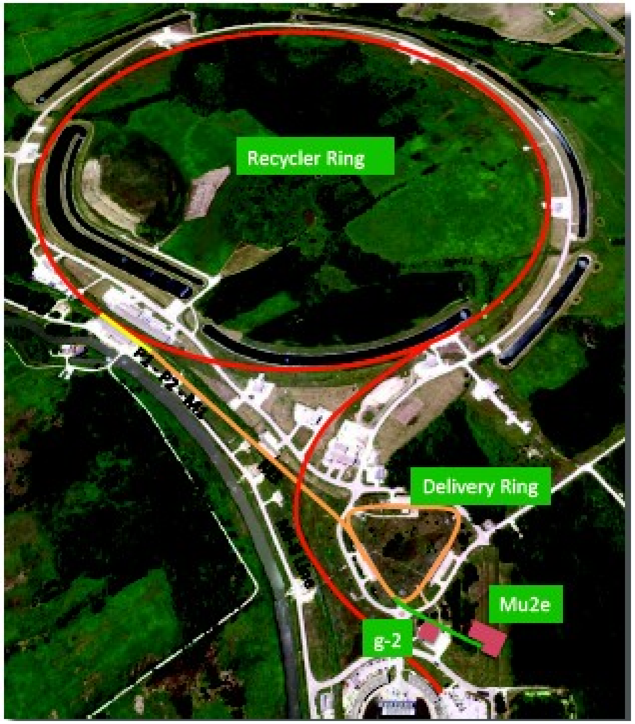
A search for **Charged Lepton Flavor Violation (CLFV)**

via the coherent conversion:

$$\mu^- + Al \rightarrow e^- + Al$$

at the Fermilab Muon Campus





The goal is to improve by **a factor 10^4** the world's best sensitivity (SINDRUM II*) on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

down to a Single Event Sensitivity of $3 \cdot 10^{-17}$

SM prediction is $<10^{-49}$-10^{-52}.

Any observation → clear evidence for **New Physics**

*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

CLFV searches

Muon sector currently provides the most stringent limits to CLFV

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	
$\tau \to \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

"3 stars" discovery capability in many theoretical frameworks

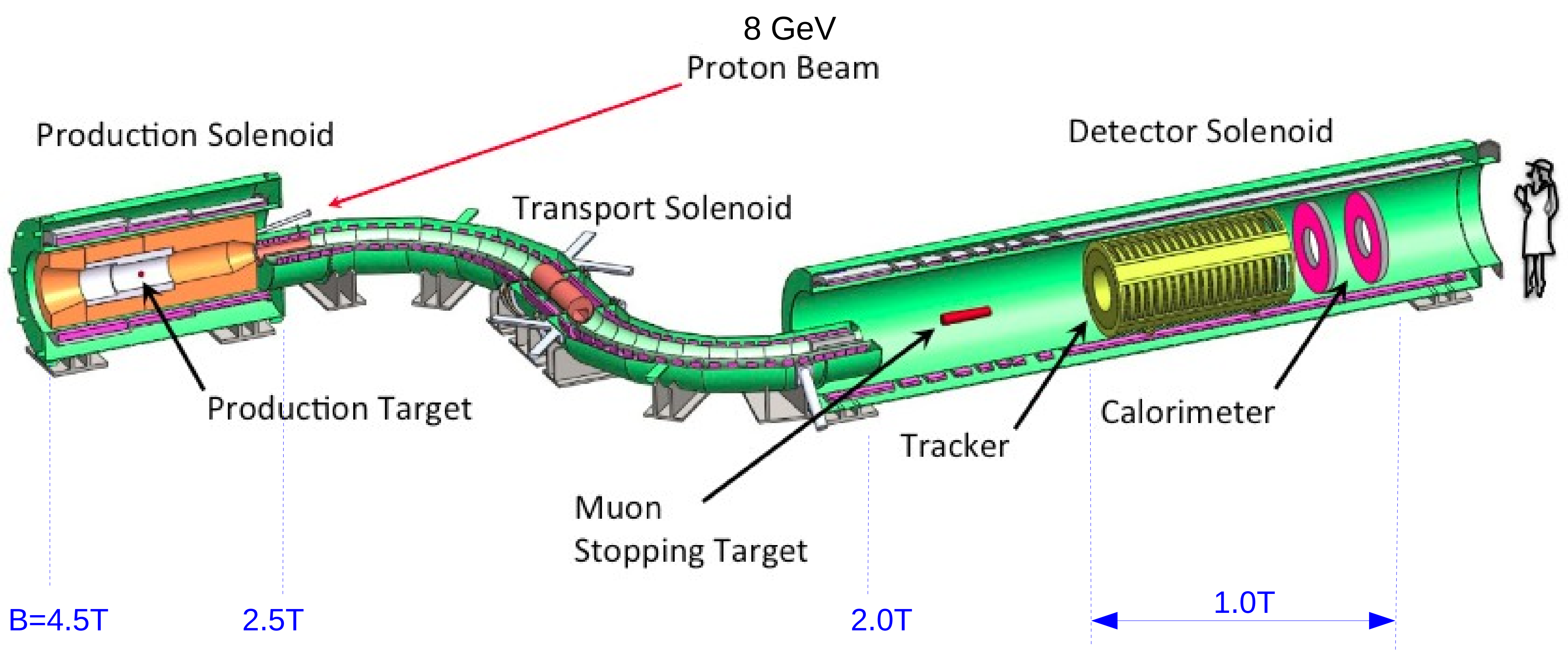
Different sensibility to different processes makes the 3 experimental searches complementary

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

W.Altmanshofer at al. arxiv 0909.1333v2

The muon beam line



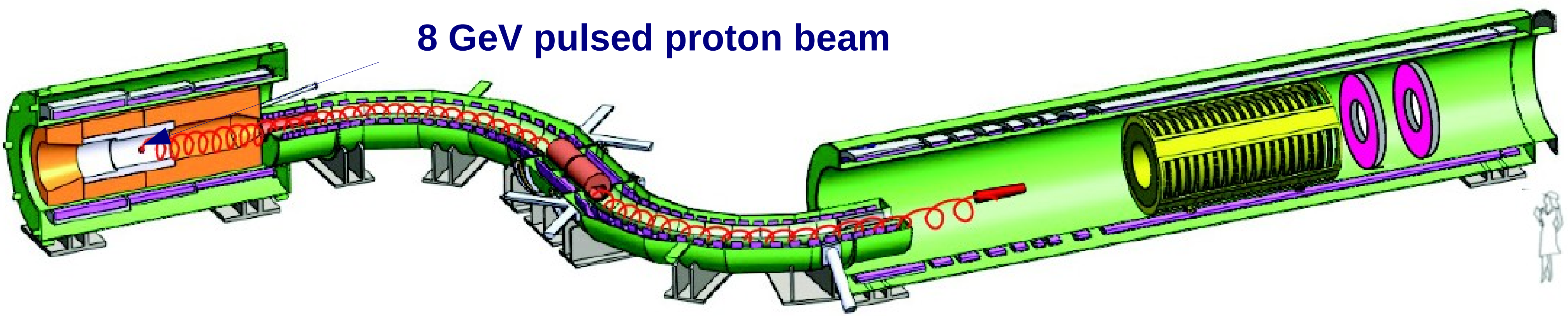
3 Superconducting Solenoids:

Production Solenoid: *tungsten target*, graded field reflects low momentum particles downstream

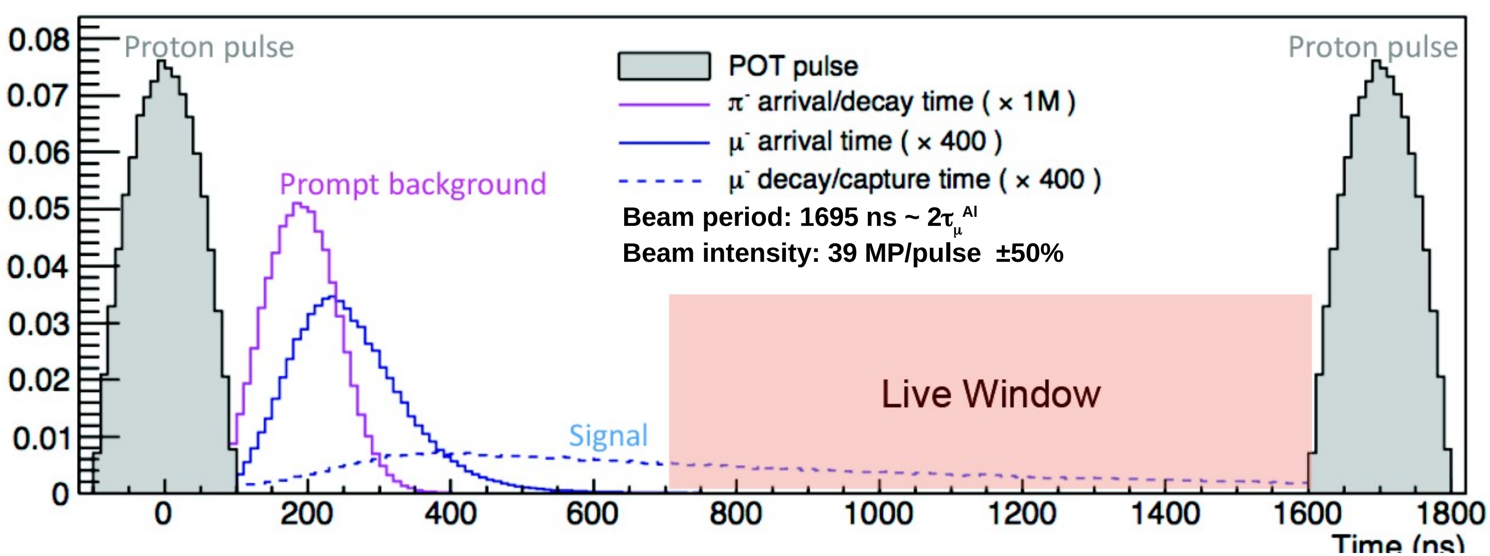
Transport Solenoid: select negative particles with the right momentum, antiproton absorber

Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors

The proton beam structure



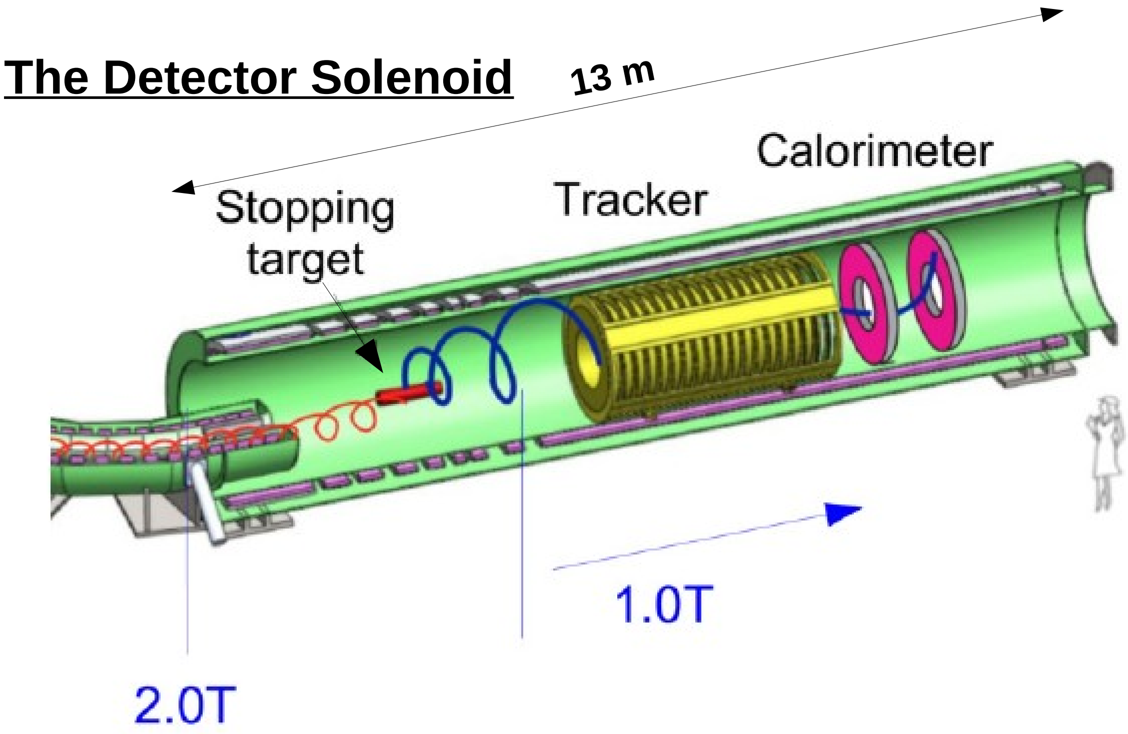
Pulsed Proton Beam Structure



Analysis window starts ~700 ns after the pulse to suppress prompt backgrounds

Extinction Factor $<10^{-10}$ (fraction of protons out of bunch)

The detectors region



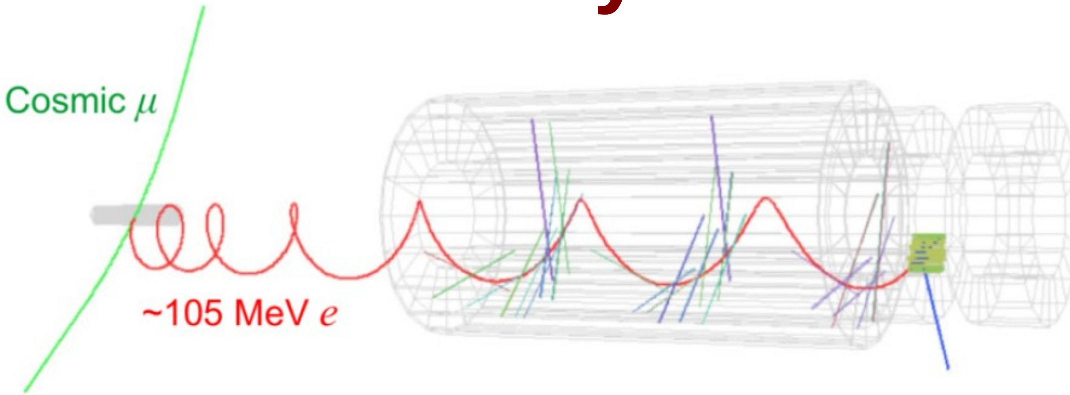
μ

The stopping target

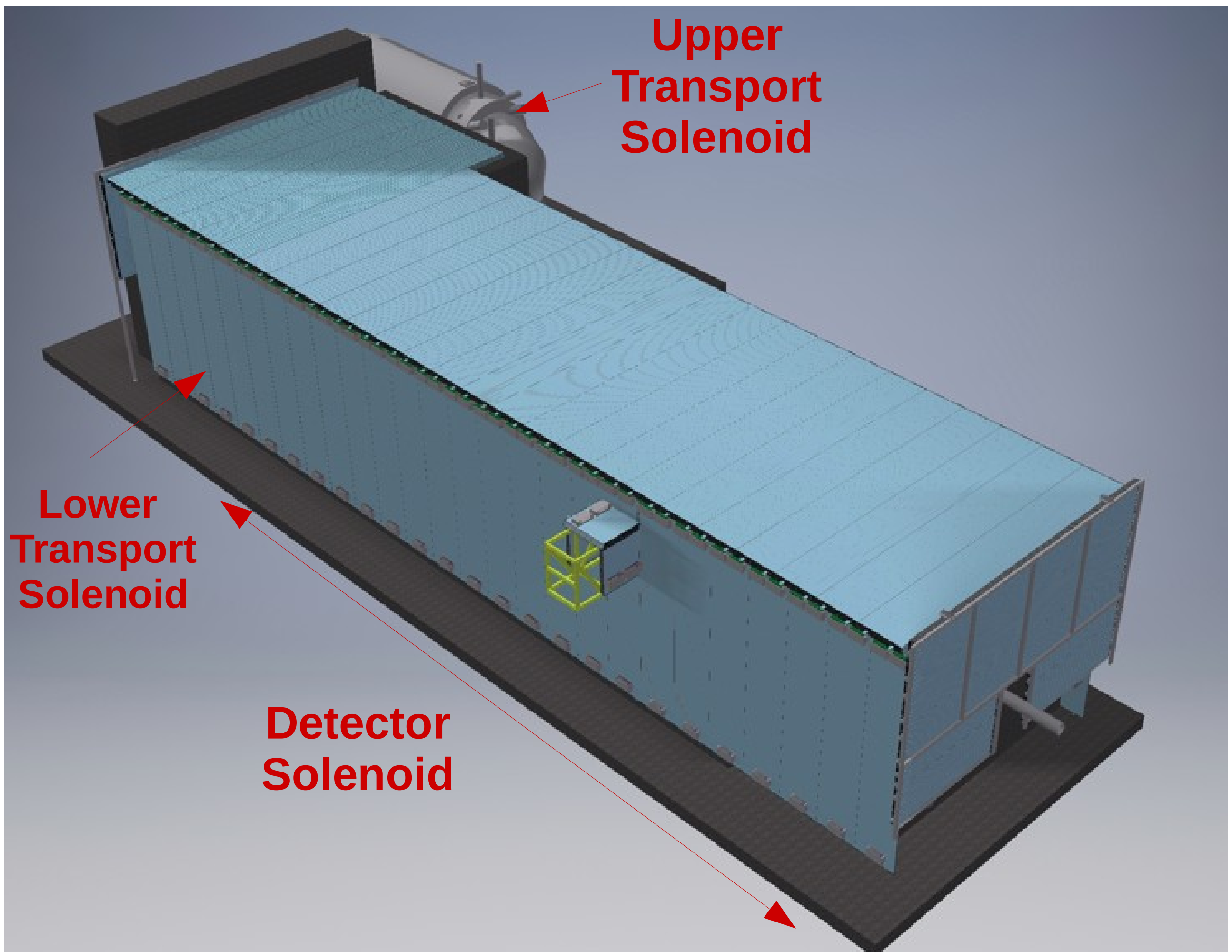
37 foils of Al
100 μm thick
75 mm radius
21 mm central hole radius

Acceptance for conversion electrons improved by magnetic gradient
Minimum amount of material before momentum measurement (segmented target and straw tube tracker)
Constant field in the tracking volume

The Cosmic Ray Veto

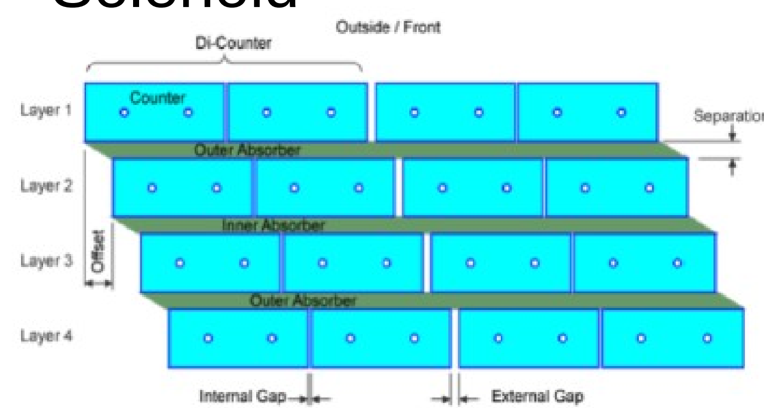


About 1 cosmic event/day emulating a 105 MeV electron



Cosmic Ray Veto:

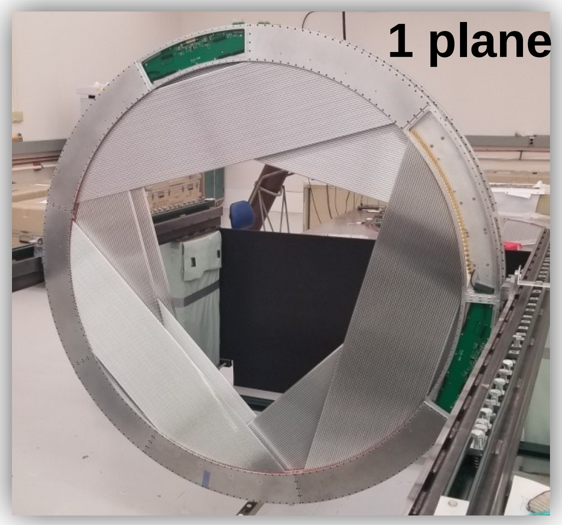
4 layers of scintillator counters covering Detector Solenoid and Lower Transport Solenoid



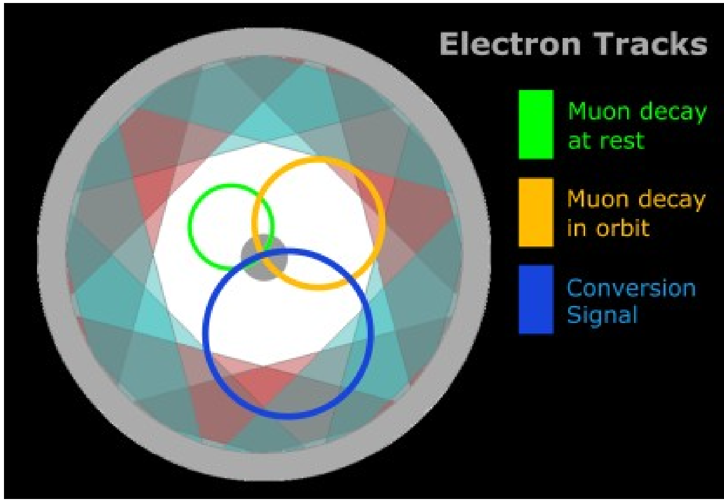
3 of 4 layers provides a veto efficiency >99.99%

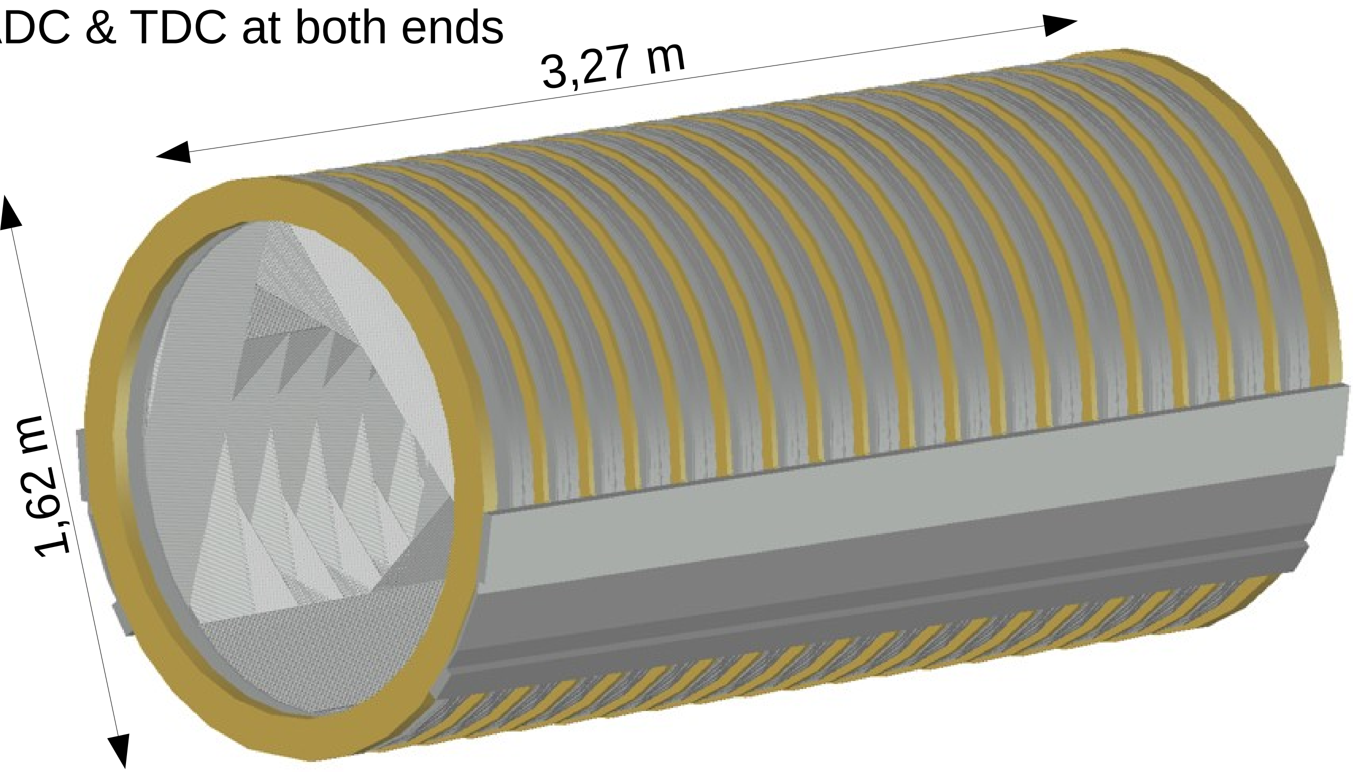
The straw tube tracker

~21000 straw tubes 15μm mylar
5 mm diameter,
80:20 $ArCO_2$ gas mixture
25 μm tungsten wire @1450V
ADC & TDC at both ends

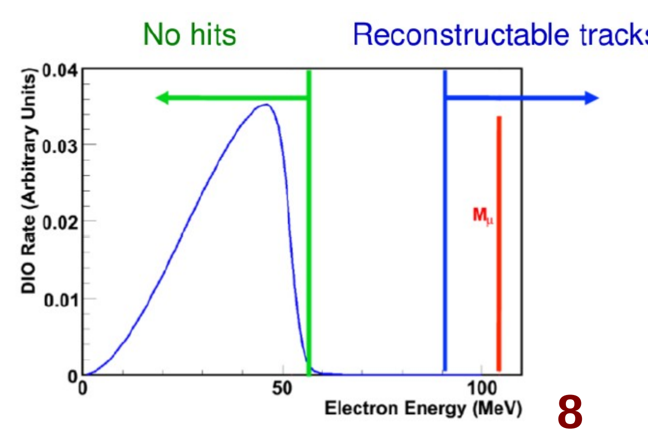


18 stations of 12 panels covering 120^o each (stereo view)

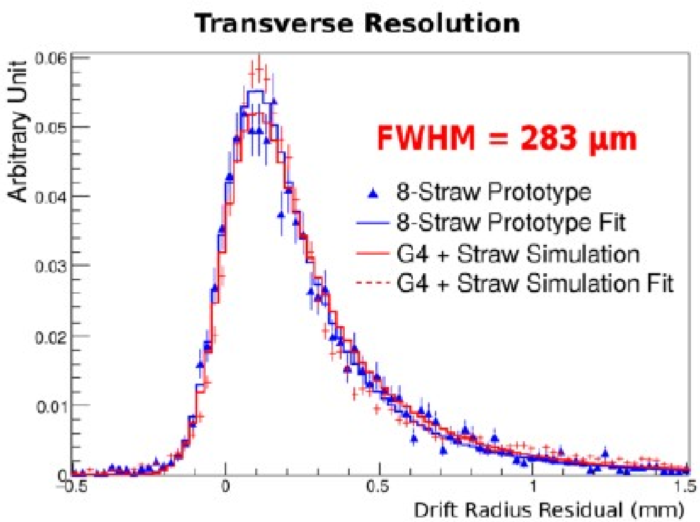


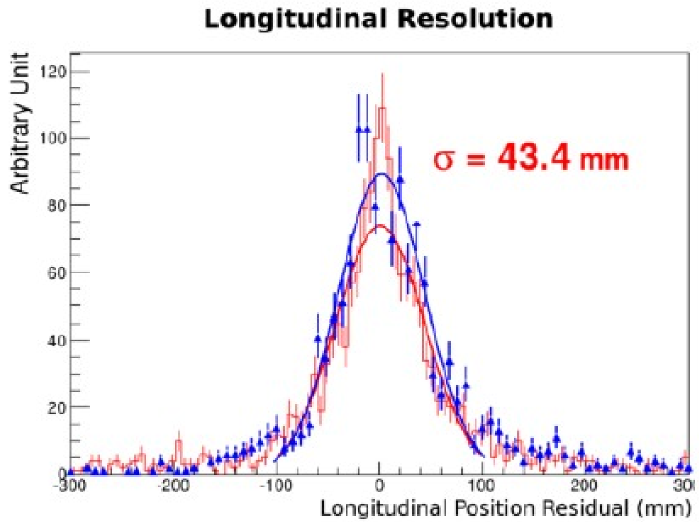


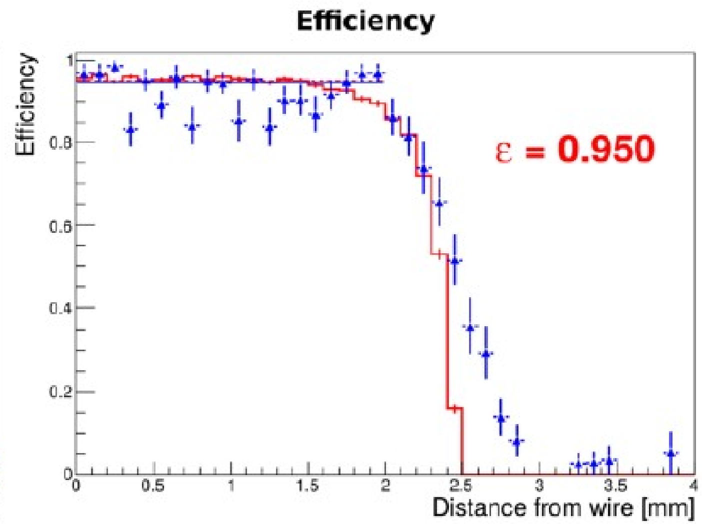
Tracker not sensitive to particles with p_T<80 MeV/c
(beam flash and most of DIOs)

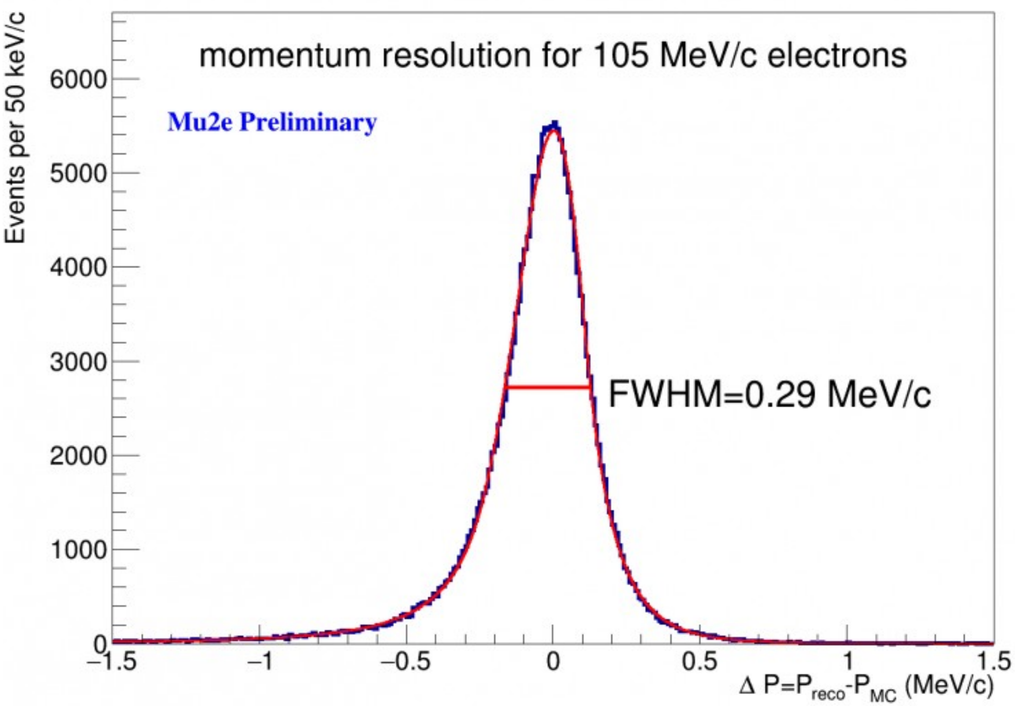


Tracker performances

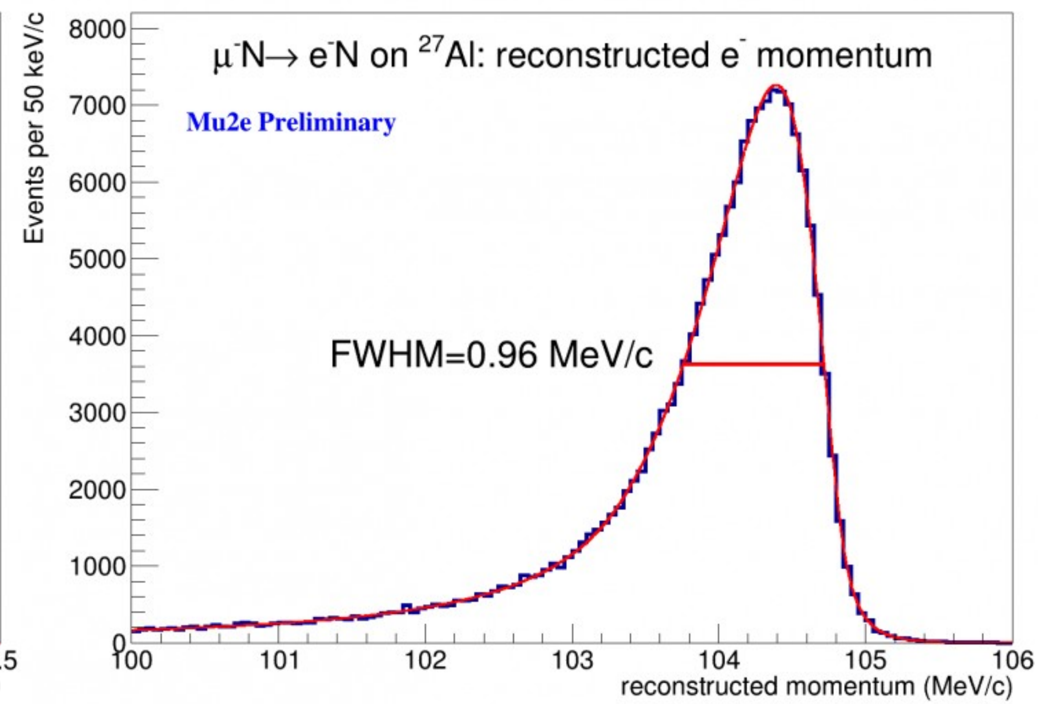






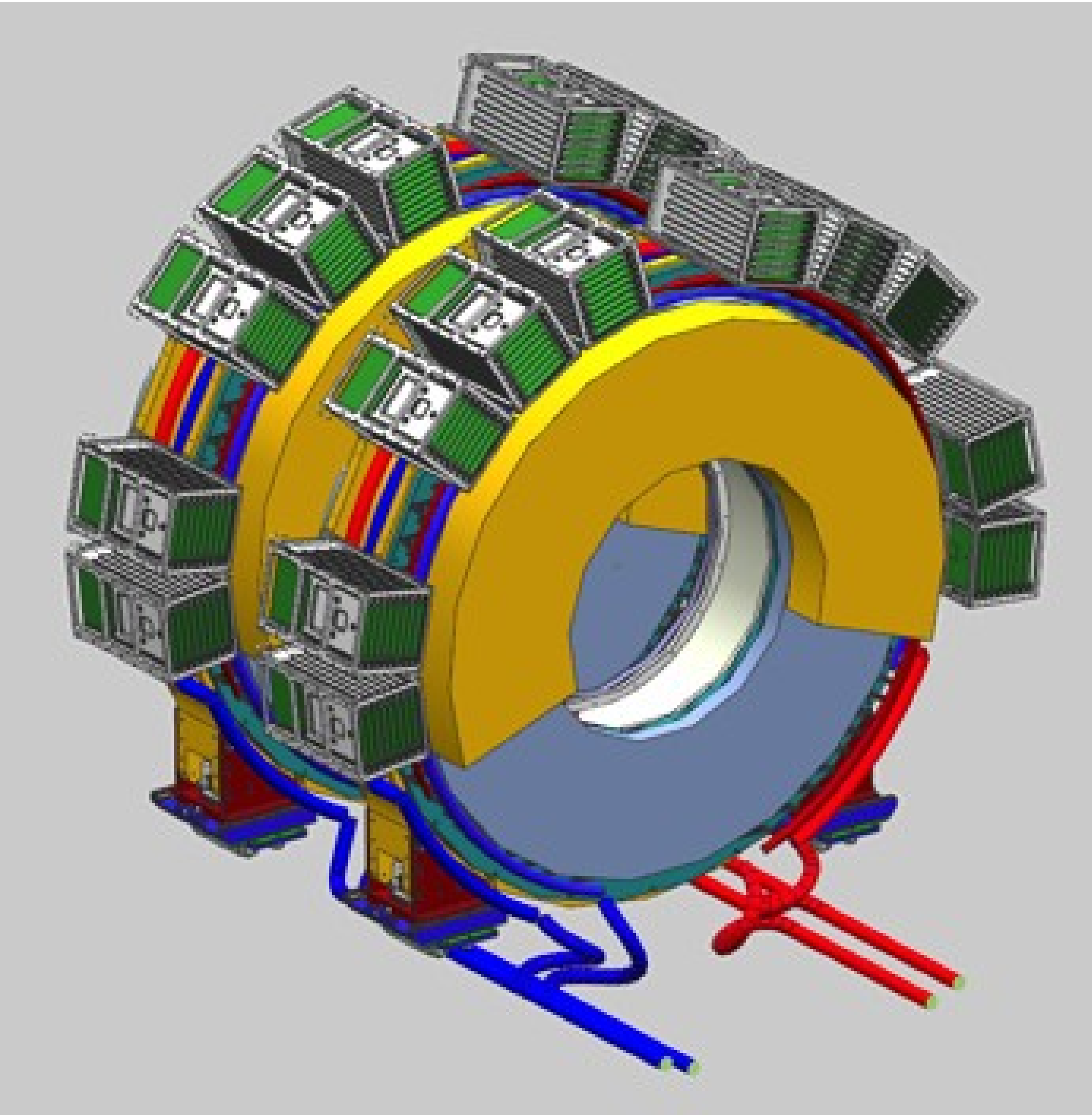


Reco-MC momentum at tracker entrance

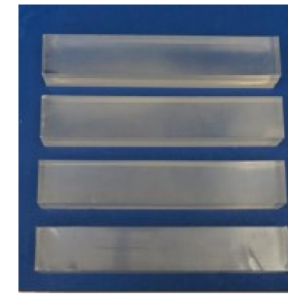


Left tail due to energy losses

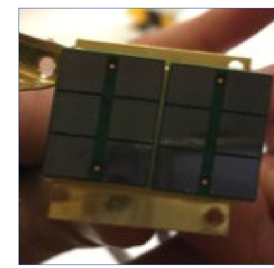
The electromagnetic calorimeter



Geometry (acceptance optimized)
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm



Active material:
pure CsI crystals
674 crystals/disk
3.4x3.4x20 cm^3



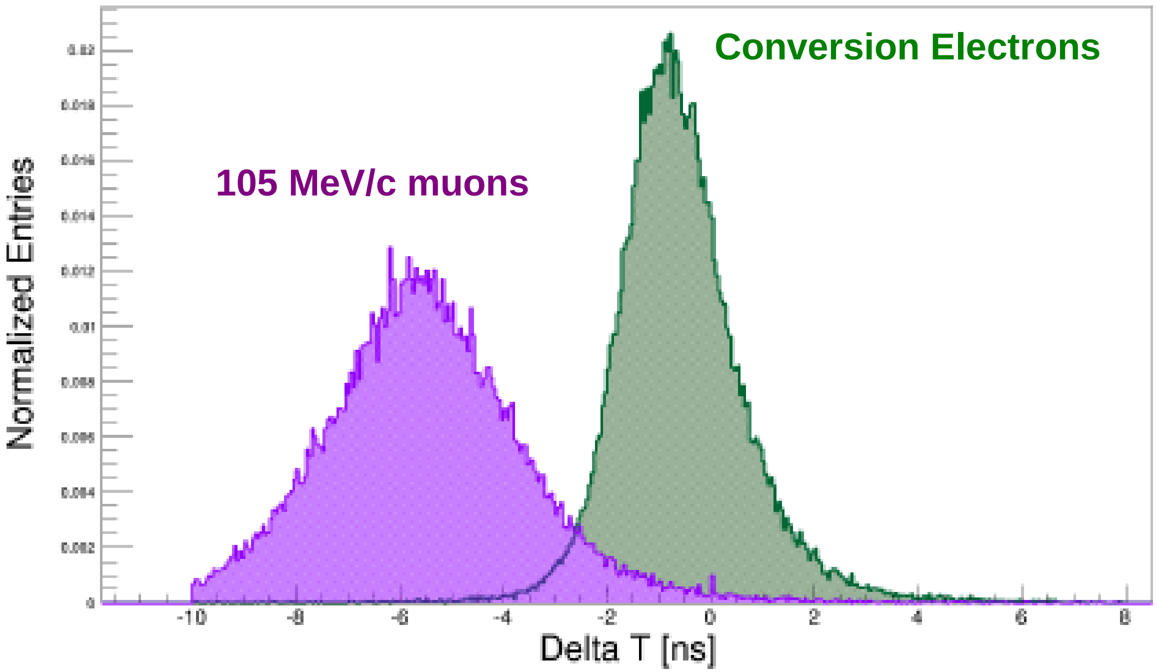
Sensors:
Arrays of 6 SiPMs
2 arrays/crystal
14x20 mm^2 each

Readout electronics:
Preamplifiers on sensors back
Voltage control and Waveform
Digitizers in crates around disks

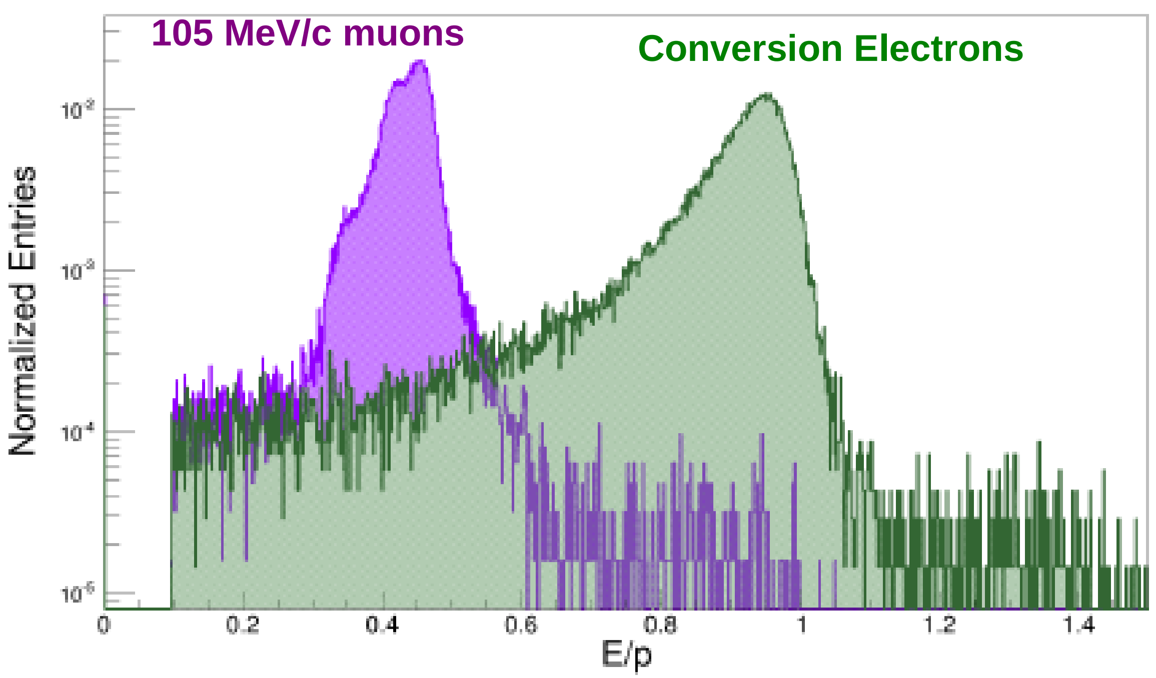
Calibration/monitoring system:
Fluorinert liquid in front of each disk
Laser and electronic pulses

See E. Diociaiuti's talk

Particle identification



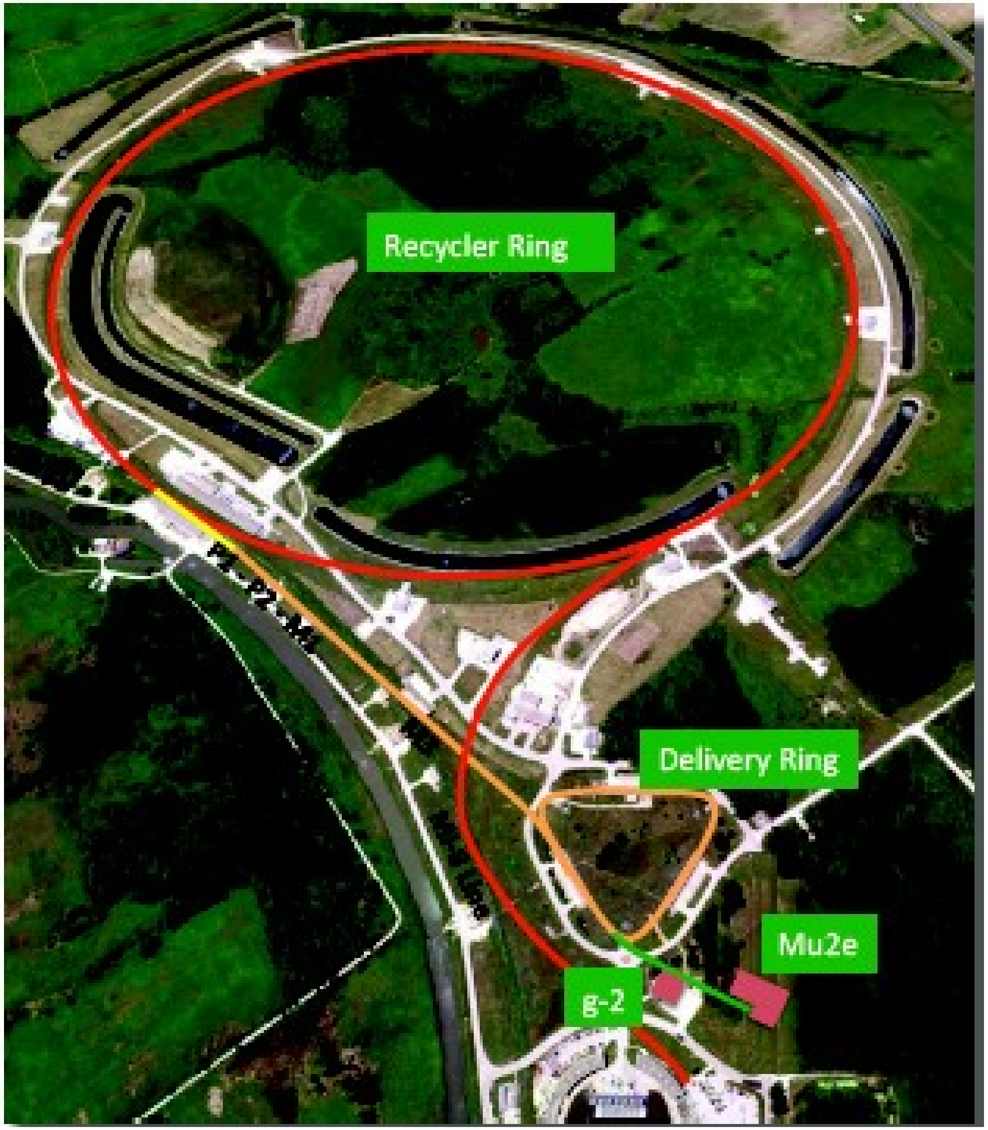
Extrapolated track time (assuming electron mass) – calorimeter cluster time



Calorimeter cluster energy / track momentum

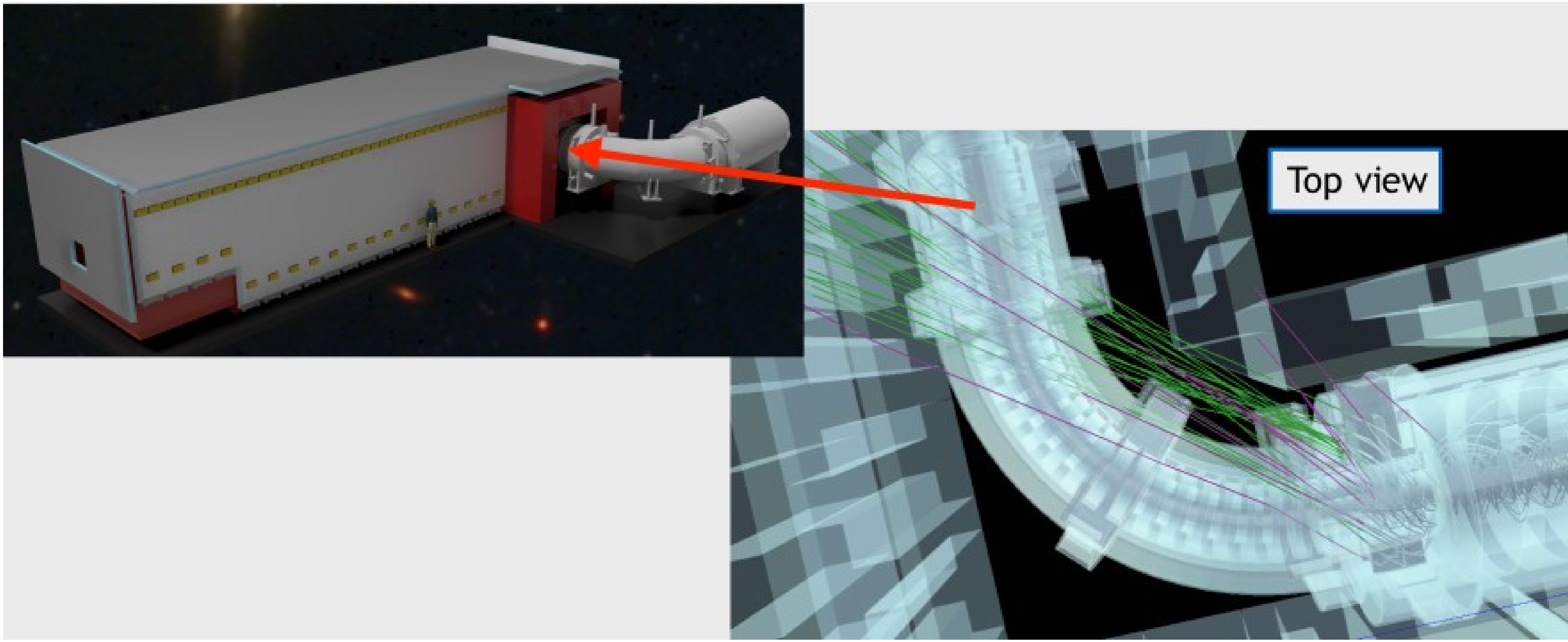
An ANN selection makes the cosmic muons background negligible wrt the cosmic electrons irriducible background

Mu2e run schedule



- Beam on target late 2024
- Run 1: 2025-2026
  - x1000 improvement over SINDRUM-II 90% CL limit
- PIP-II/LBNF shutdown scheduled for end of 2026
- Data-taking resumes early 2029
  - The goal is a x10000 improvement over SINDRUM-II: (90% CL)

Irreducible cosmic background

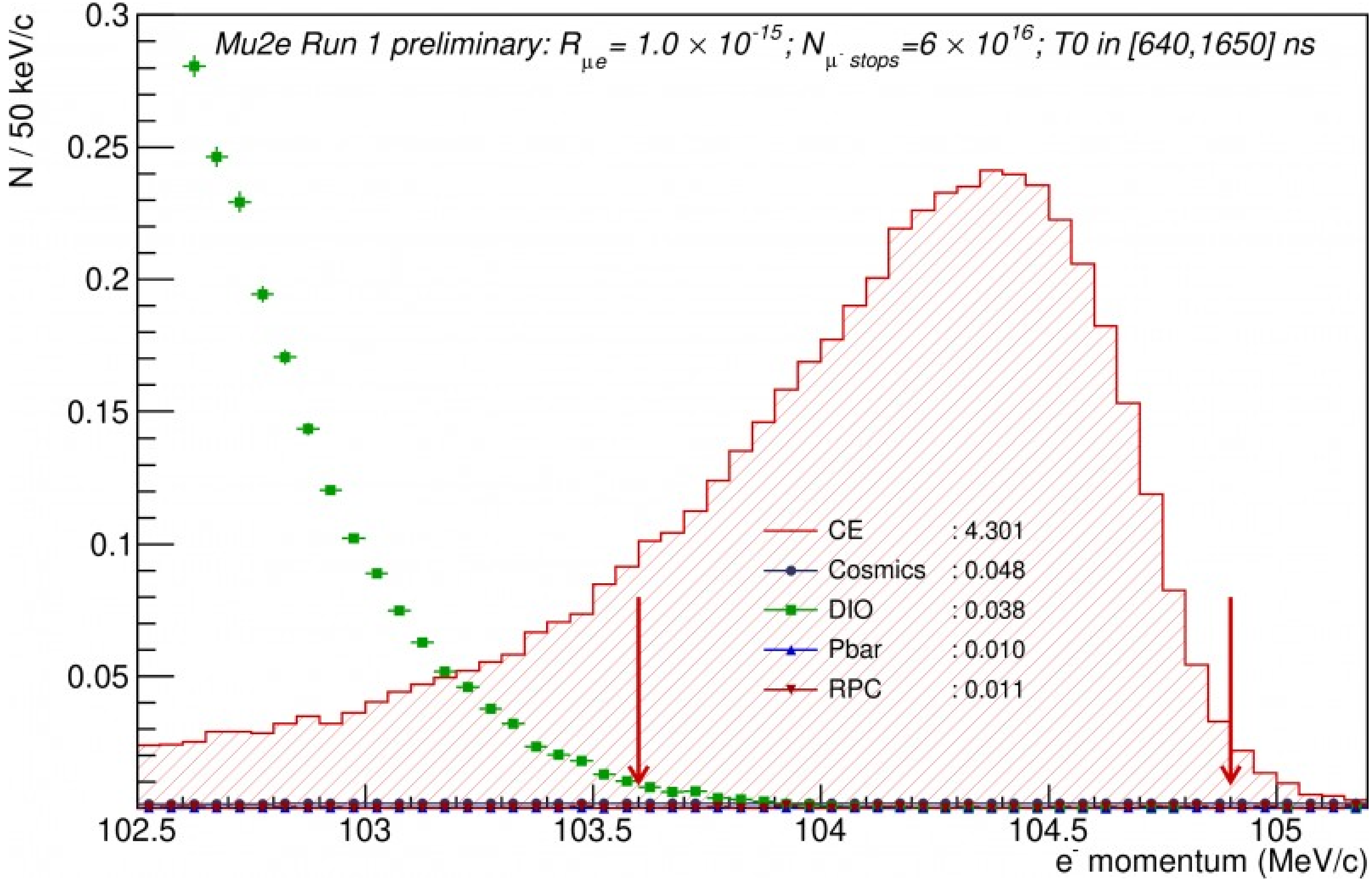


The TS region cannot be completely covered

The dominant cosmic background is due to muons entering through the TS hole and producing a delta ray electron when interacting with the TS material.

Cosmic background is the dominant background for CE search

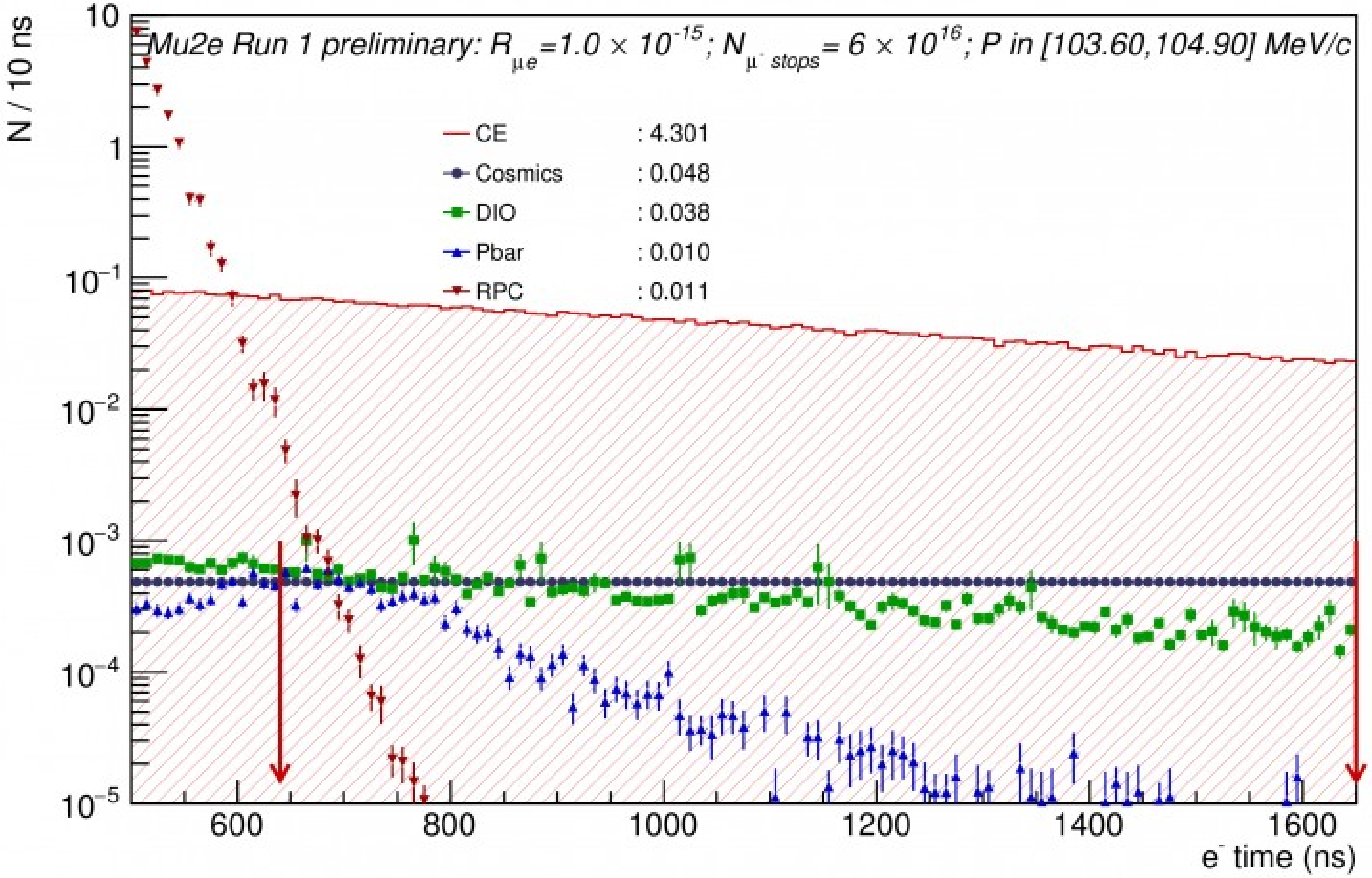
Decay in orbit (DIO) background



The DIO spectrum falls as $(E_{max}-E)^5$ close to the end point

Can be suppressed by the momentum window cut

Other main backgrounds



Antiproton background is suppressed by a set of passive absorbers

Radiative Pion Captures in the Al target producing photons converting in e^+e^- pairs can be suppressed by a time window cut

Time and momentum cuts optimized to get the best sensitivity

Conclusion

- CLFV sensitivity in the muon sector is expected to be improved in the very next future by the experiments looking for $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ or $\mu N \rightarrow eN$. If a violation will be observed in any of these processes, it will be very important to have the complementary information from the other two to investigate the origin of the violation
- Mu2e will improve by 4 order of magnitudes the current world sensitivity on muon conversion to electron
- Prototypes test and simulation are confirming the design detector performances
- Construction of the beam line, solenoids and detectors is under way
- First run in 2025-2026 will allow to improve SINDRUM II limit by x1000

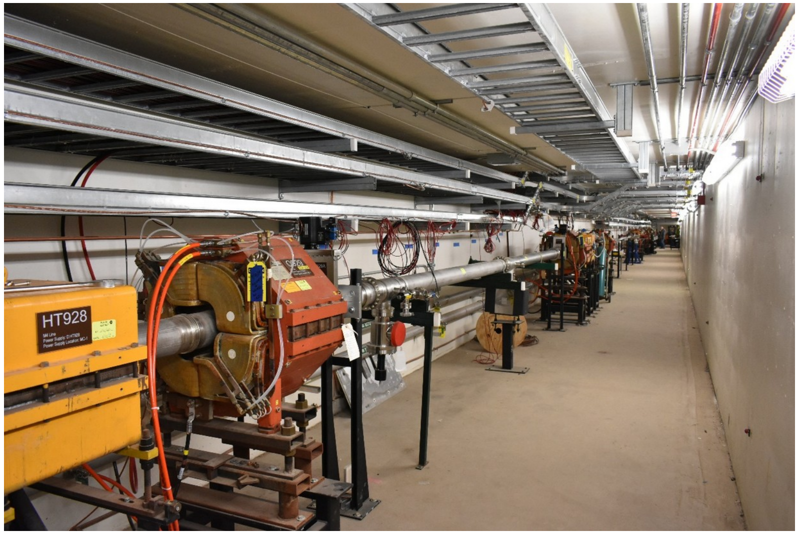
Backup

Mu2e status: detector hall

Mu2e status: beam line

M4 beamline completed up to the diagnostic absorber

Final focus installation is in progress



M4 beam line

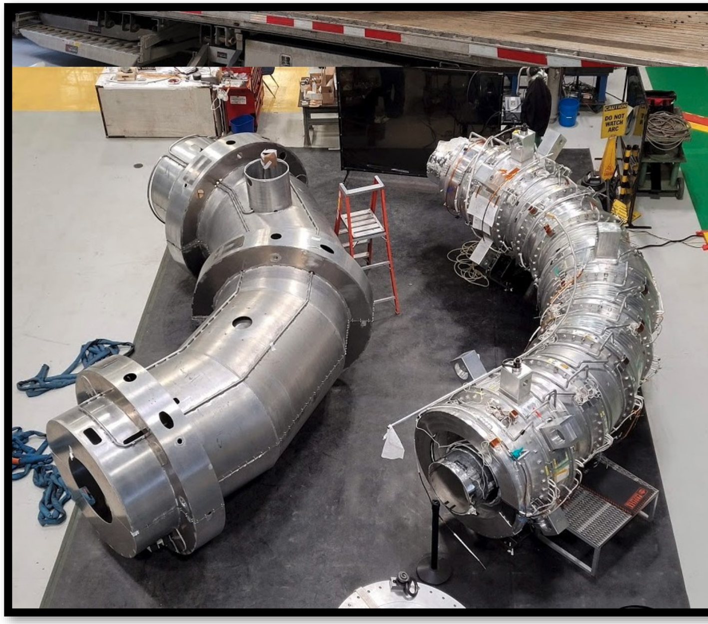
Diagnostic absorber wall

Final focus: large quadrupoles

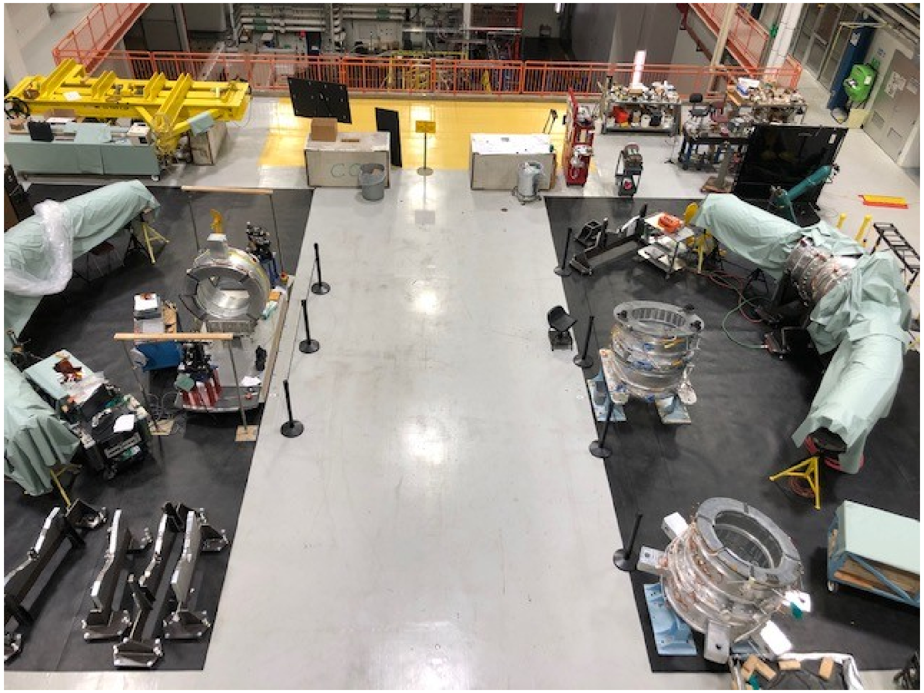
Mu2e status: transport solenoid

TS Coils at ASG

All coils produced at AGS (Genova, Italy)



Tsu cold mass and thermal shield



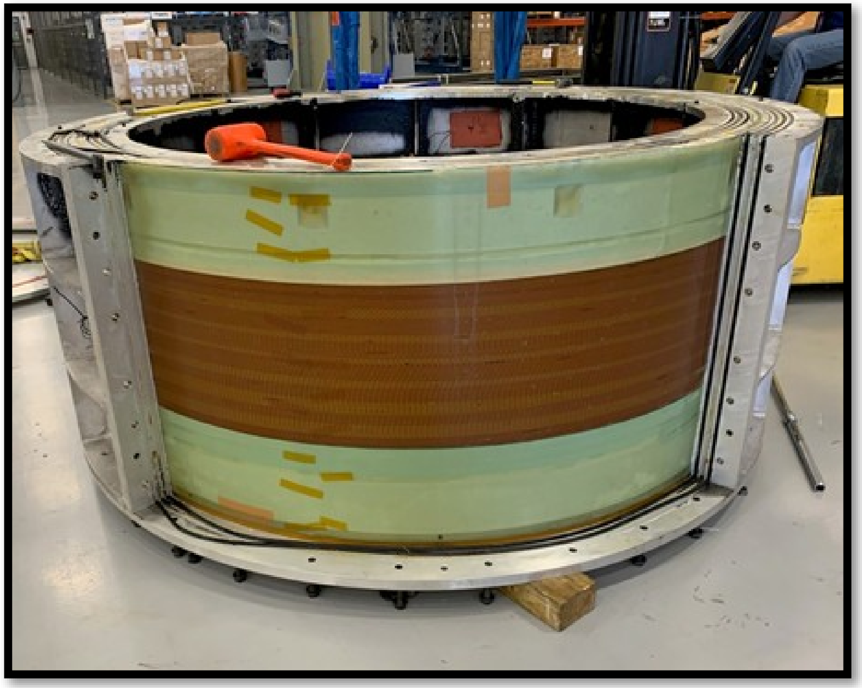
Fermilab Test Facility

Mu2e status: production/detector solenoid

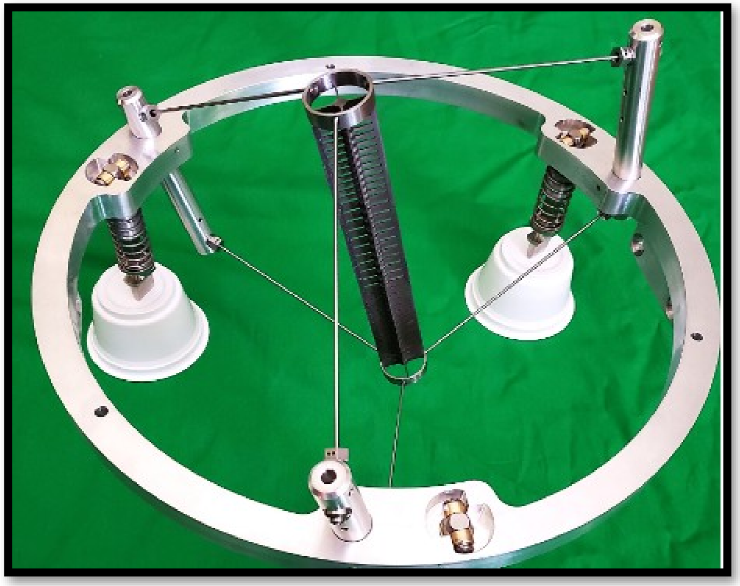
In production at General Atomics (Tupelo, US)

First DS module completed!

DS10 module



PS1 coil

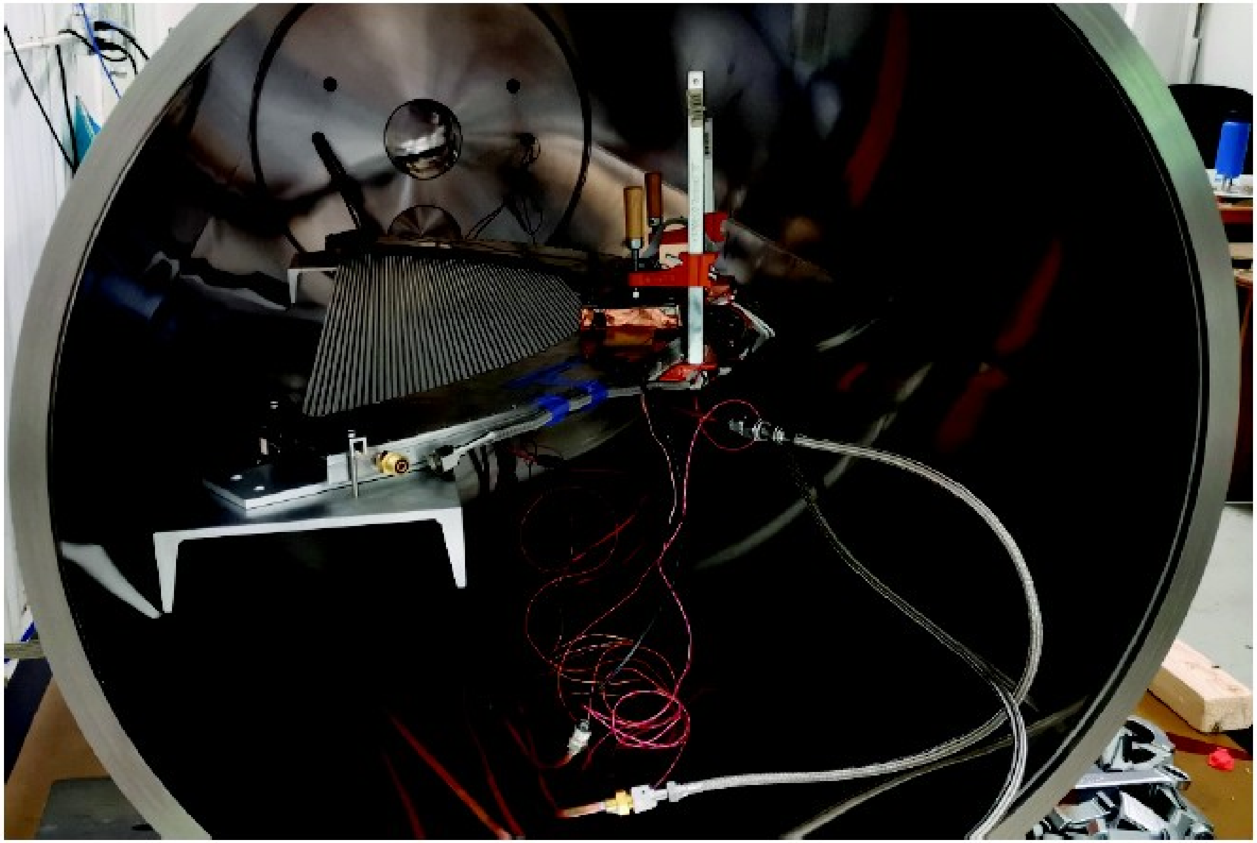


Production Target

Mu2e status: tracker

Straws production almost completed
46% of panels assembled
(estimated time for completion Nov 2022)

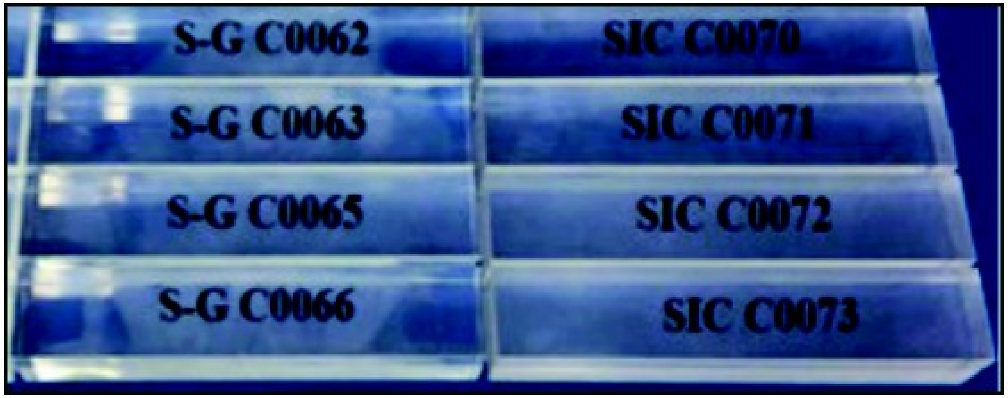
Panel assembly at U. of Minnesota



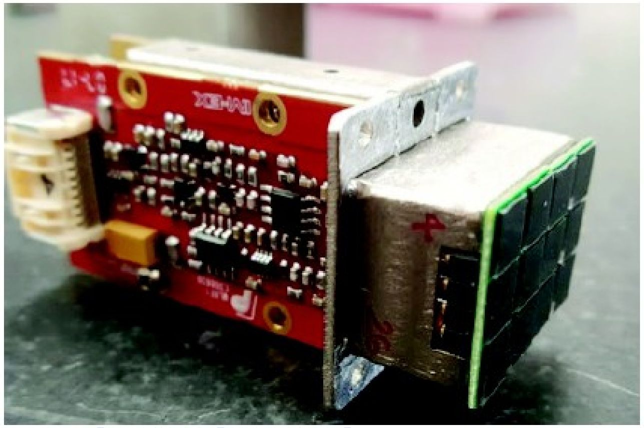
Panel vacuum test at Fermilab

Mu2e status: calorimeter

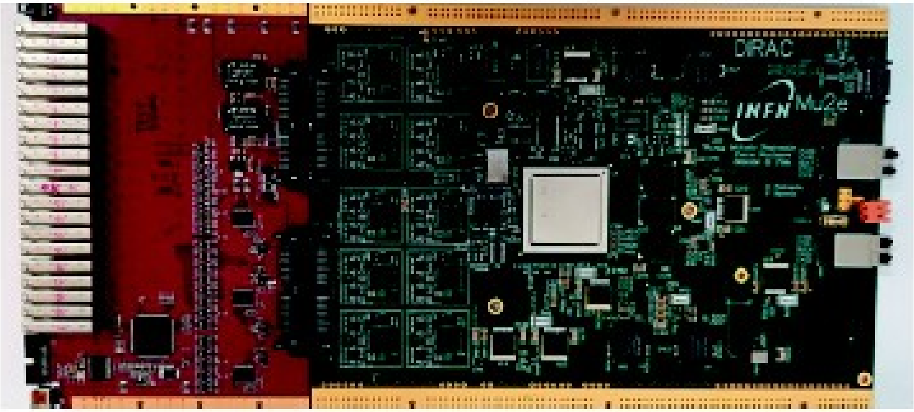
All SiPMs and crystals produced and qualified
Radiation hard electronics tested, starting production



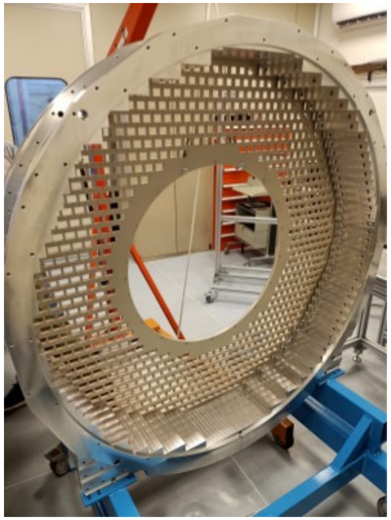
CsI crystals



FEE boards + SiPM arrays

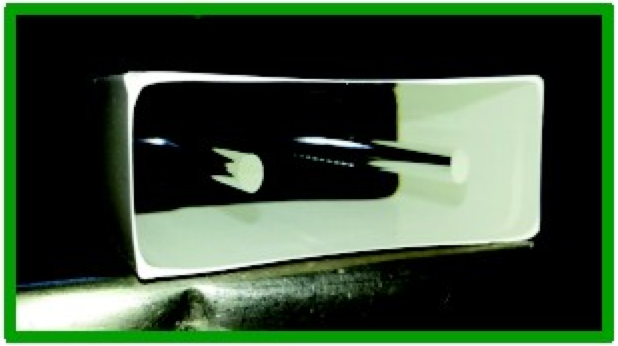


Voltage control and Digitizer board



External disk and back plane

Mu2e status: cosmic ray veto



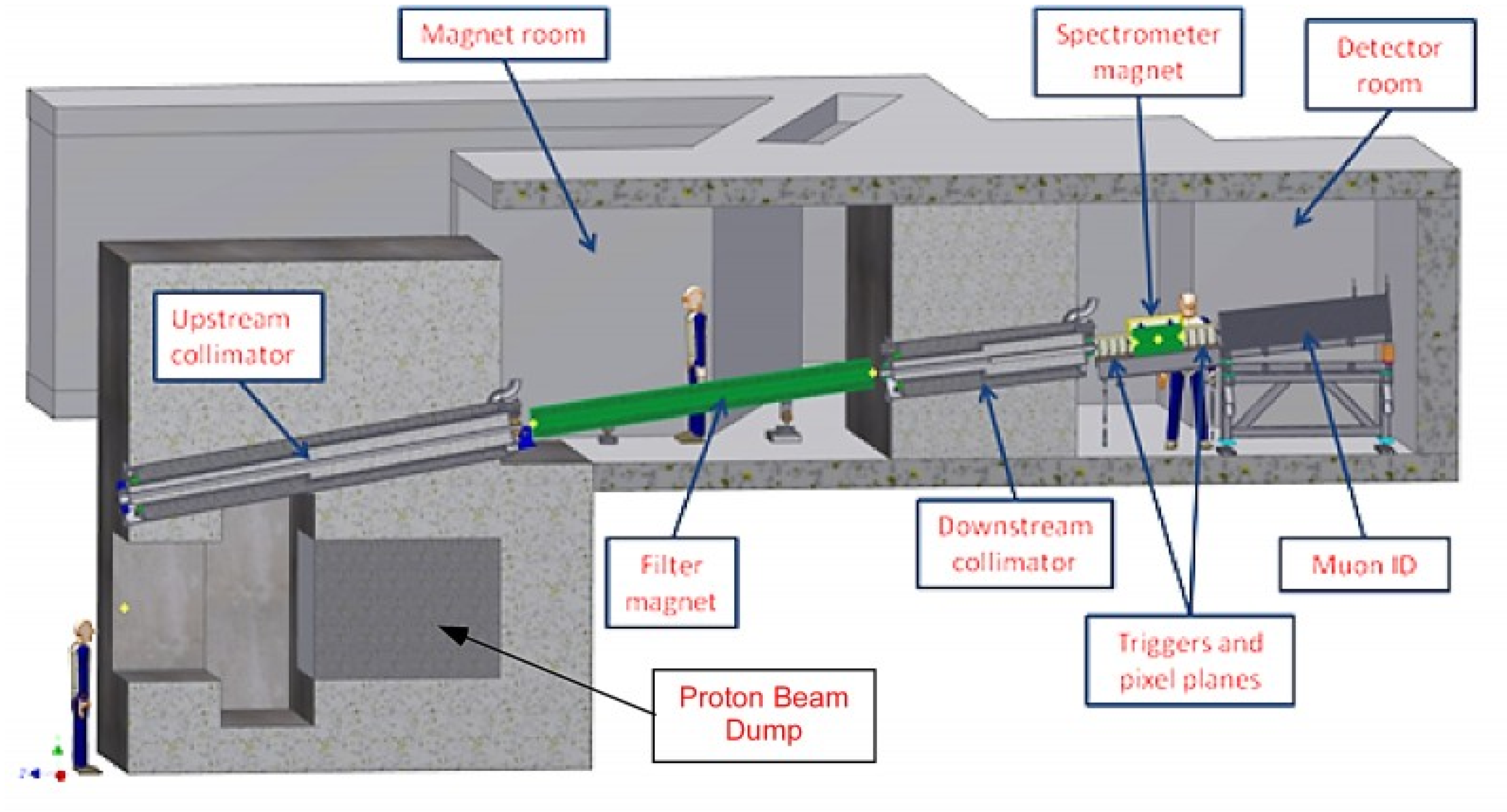
CRV counter

4 layer modules at U. of Virginia

Half of the modules produced

Expected completion by the end of 2022

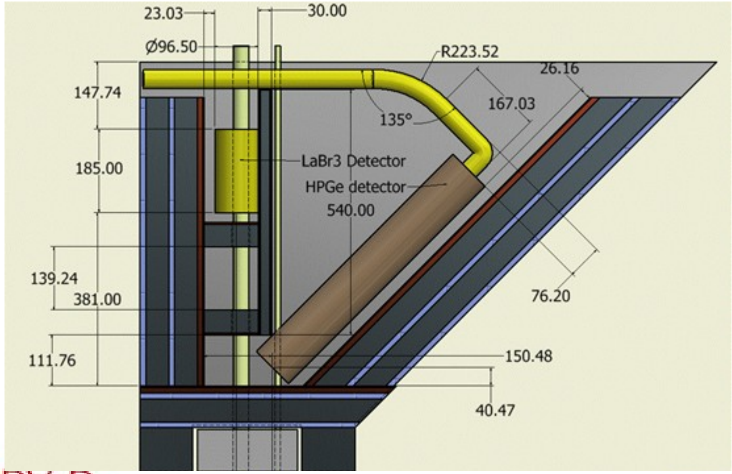
Extinction monitor

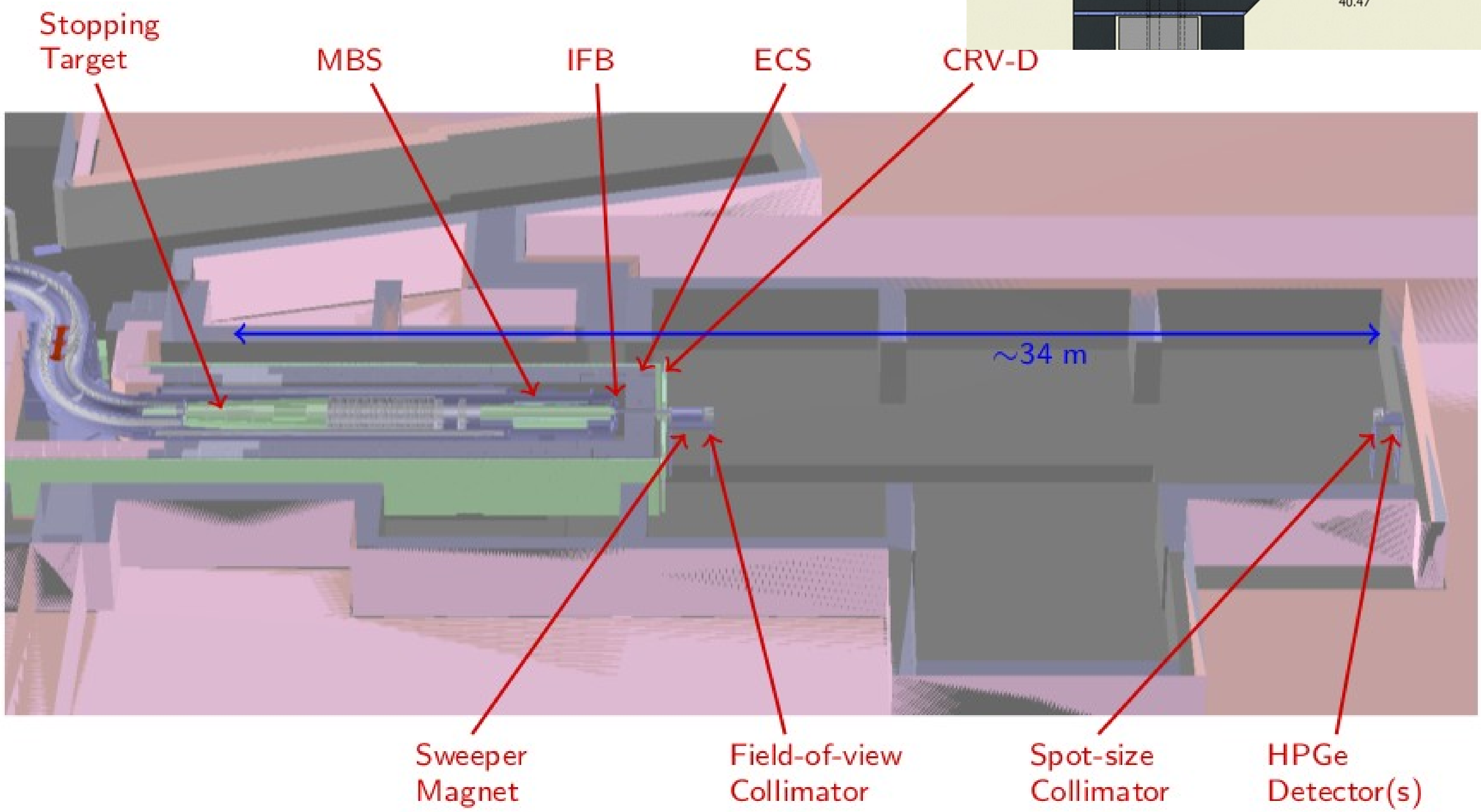


Validates the assumption of an extinction factor $<10^{-10}$

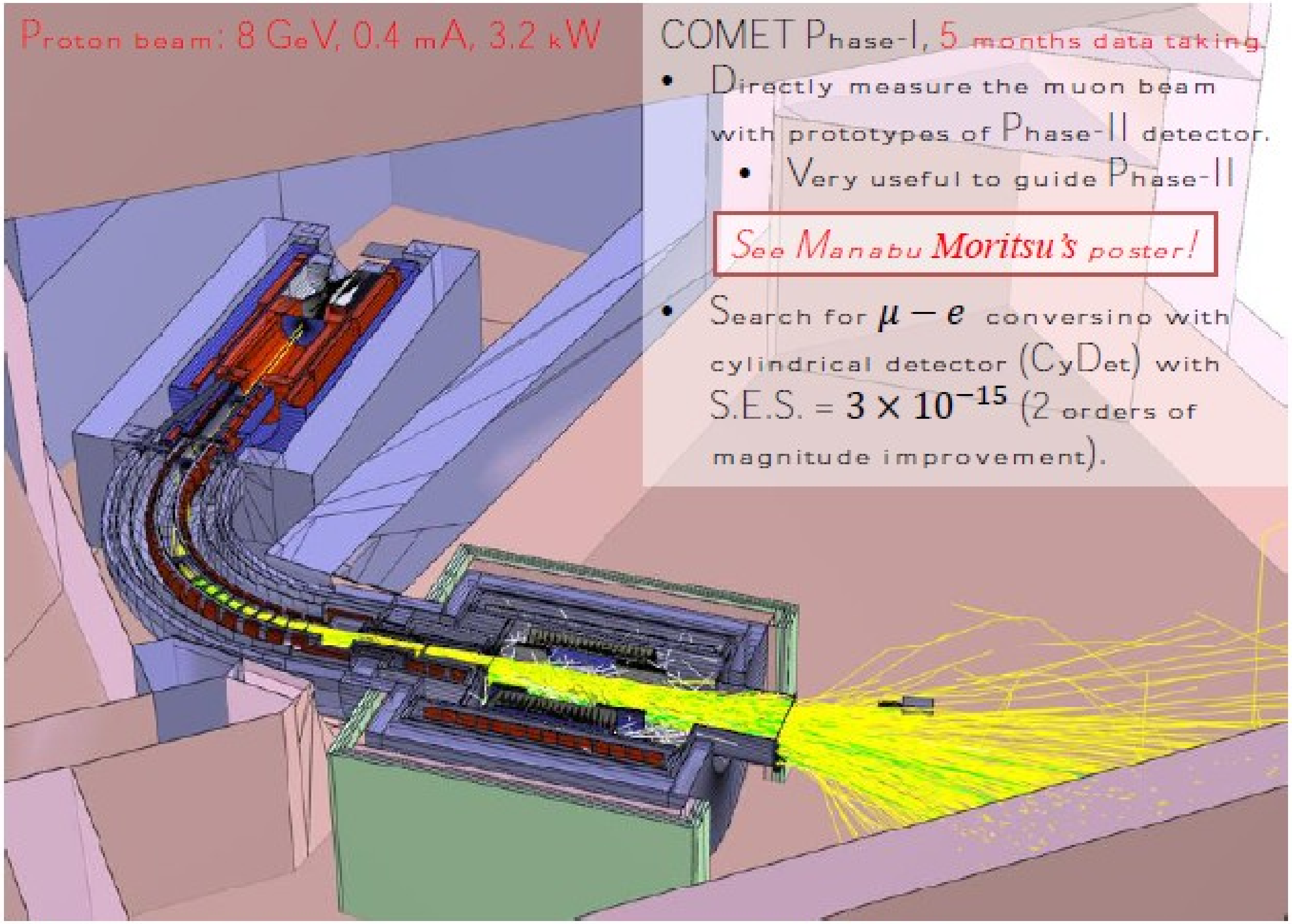
Stopping target monitor

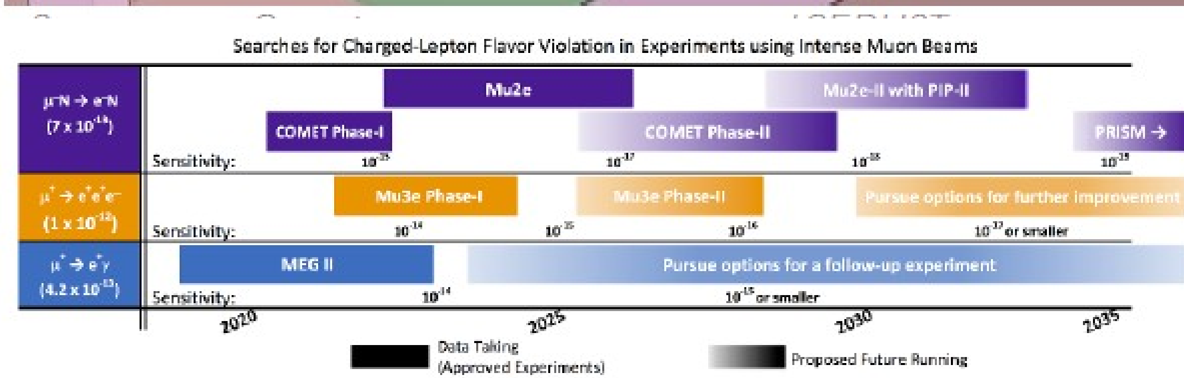
Ge and LaBr detectors to detect the monochromatic X and γ rays produced by muon captures in Al with a statistical error <10%





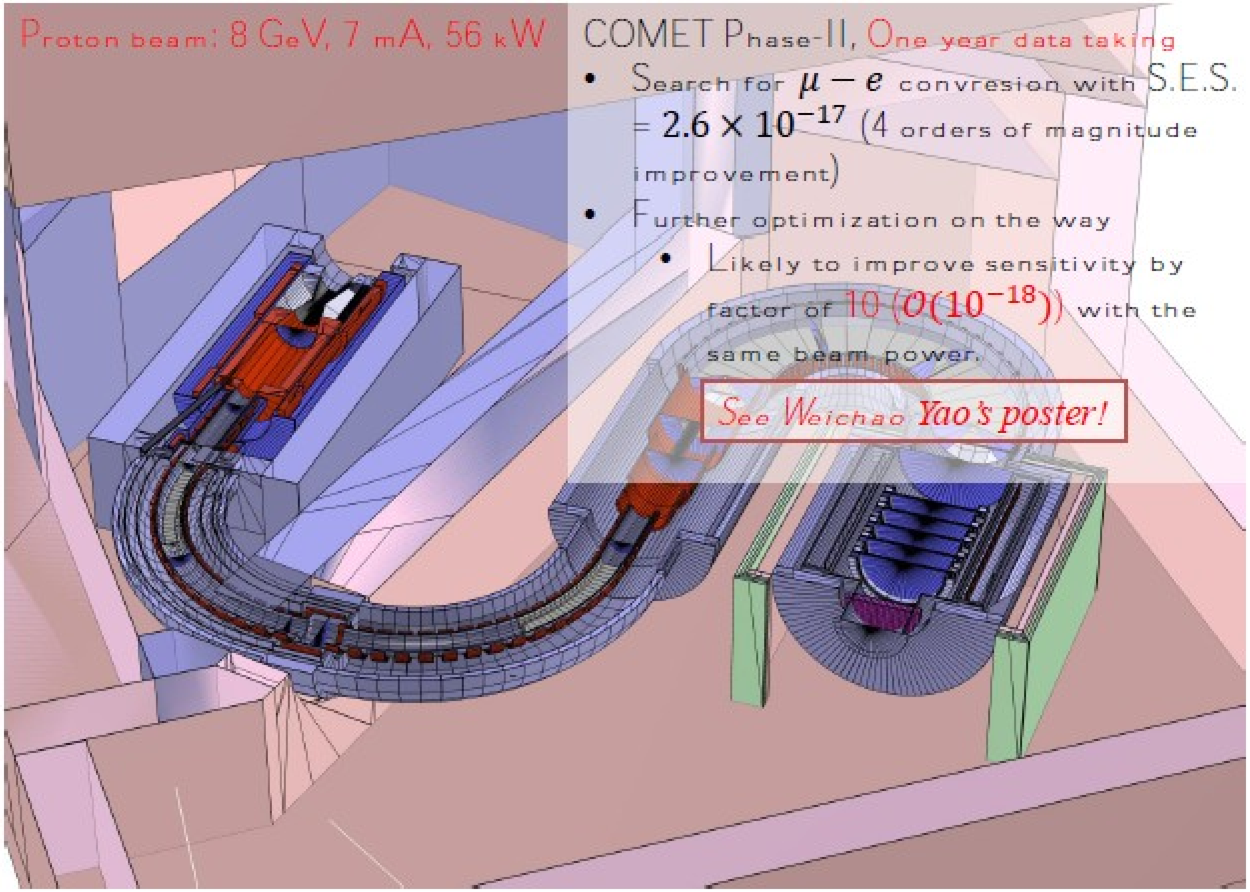
COMET Phase I





From Wu Chen's presentation at CLFV2019

COMET Phase II



From Wu Chen's presentation at CLFV2019